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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A range of ZnO-on-silicon surface acoustic wave devices have been fabricated and tested. Both diode and magnetion rf sputtering was employed. A new transducer for the monolithic configuration was reported which permits increased operating frequencies. The first SAW resonator on silicon was constructed and operated. Both high Q and excellent temperature stability was observed.

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Interim Scientific Report
1 June 1981

MONOLITHIC ZnO SAW STRUCTURES

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RESEARCH OBJECTIVES

Introduction

The role of monolithic surface acoustic wave (SAW) devices in performing the "real-time" analogue of nonlinear signal processing functions is by now widely accepted. Monolithic structures are intrinsically rugged, reproducible, and compatable with modern integrated circuit fabrication techniques. The emphasis of the research reported herein involves the evaluation of monolithic SAW structures and materials, with the research treating in large part modified structures and prototype device concepts.

Specific Tasks

1. An important consideration in the ultimate application of SAW signal processing devices to real systems is the available bandwidth. As a consequence, a major aspect of the project involves measures aimed at increasing the available bandwidth of monolithic SAW devices.

2. ZnO has proven to be an acceptable piezoelectric material for the implementation of monolithic, "on-silicon" device concepts. An alternate material, AlN, has been proposed as representing a possible improvement over, and replacement for ZnO. A portion of the project has been devoted to an examination of AlN for monolithic SAW applications.

3. It has been established that the electrical properties of the $Si\text{-}SiO_2$ subsystem are adversely affected by the ZnO deposition process. Methods for minimizing the effects of the sputtering damage are being examined and evaluated. Also, an instability related to the injection of electrons from the metal gate electrode into the underlying ZnO is observed upon applying a d.c. gate bias. We are seeking an understanding and constructive control or blocking of this injection process.

4. A wide range of analog linear and nonlinear signal processing functions are now feasible as a result of continuing developments in acoustic surface wave techniques. Under investigation are problems associated with achieving practical devices, such as correlators and resonators, using the monolithic technology.

STATUS OF THE RESEARCH EFFORT

A. Bandwidth Considerations

A significant improvement in fractional bandwidth obtainable with monolithic SAW devices resulted from our previously reported work with Sezawa wave propagation. In an effort to further increase the actual device bandwidth, we have addressed the problems associated with operation at higher frequencies. A major obstacle to reaching shorter wavelengths involves the problems encountered in fabricating structures having very small dimensions. We have succeeded in demonstrating a means for significantly increasing the yield for SAW transducers in the monolithic configuration by use of a pair of "single phase" transducers. Our work with this transducer configuration has been submitted for publication, and a preprint is included as Appendix A of this report.

B. New Materials

We are the first group to report the low temperature ($\sim$ 200°C) growth of SAW device-quality piezoelectric films of AlN on silicon. Reactive magnetion sputtering was used in a method first reported by Shiosaki who deposited such films on saphire and glass. Initial measurements of two-port insertion loss indicated values of 23 db at center band. We have also demonstrated convolution using an AlN/silicon device. These new results are presently being organized into publication form.

C. Charge Injection

In the previous annual report we reported the completion and publication of a detailed investigation into the charge injection phenomena. These charge injection studies revealed all of the injected charge becomes localized in deep level traps at the $ZnO-SiO_2$ interface under normal operational conditions. Also, a positive charge layer and associated ZnO surface barrier was found to exist in the vicinity of the $ZnO-SiO_2$ interface. The charge injection model formulated in accordance with experimental observations explained both the operational characteristics of the structure and the transient aspects of the injection process.

As an outgrowth of the cited charge-injection studies we have very recently succeeded in attaining the long-standing goal of fabricating bias-stable MZOS-SAW devices. This rather exciting development is still being investigated and verified. Details will be presented in subsequent publications and summaries.

D. ZnO-on-Si Resonators

We have recently reported the development of the first VHF/UHF resonators on a silicon chip. It was found that such devices, constructed with available ZnO films, could exhibit Q values as high as 10,000 for these first test devices. Of even greater significance, however, was the demonstration of temperature stability comparable to ST quartz SAW resonators. The observed temperature stability resulted from the use of a compensating layer. It is important to emphasize that the

compensating layer used is thermal silicon oxide. The performance of resonators using both metal and etched groove reflectors has been published, and reprints are included as Appendicies B and C.

E. Minimizing Sputtering Damage

It has long been a contention that monolithic ZnO-on-Si technology was compatable with integrated circuit fabrication techniques. It has also been observed, however, that the ZnO thin film deposition process can lead to radiation damage in the underlying Si-SiO_2 subsystem. During the reporting period the "compatability contention" was tested by fabricating MOS-transistors on a silicon substrate and then testing the device characteristics before and after the ZnO deposition process. As long as the MOS gated region was protected by a metal overlayer during the ZnO magnetion sputtering very little damage was observed in the MOS transistor characteristics.-- The MOS transistor I_D-V_D characteristics were essentially identical before and after sputtering. Thus, if magnetion sputtering is employed with active regions protected by metal overlayers, radiation damage can be minimized and the ZnO-on-Si/IC technologies are compatable.

PUBLICATIONS

M. R. Melloch, R. L. Gunshor, C. L. Liu, and R. F. Pierret, "Interface Transduction in the $ZnO-SiO_2-Si$ Surface Acoustic Wave Device Configuration," Appl. Phys. Lett., 37, 147 (1980).

S. J. Martin, R. L. Gunshor, and R. F. Pierret, "Zinc Oxide on Silicon Surface Acoustic Wave Resonators," Appl. Phys. Lett., 37, 200 (1980).

S. J. Martin, R. L. Gunshor, and R. F. Pierret, "High Q, Temperature Stable ZnO-on-Silicon SAW Resonators," Proceedings of the 1980 Ultrasonics Symposium, p. 113.

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APPENDIX A

Single Phase and Balanced Separate Comb Transducer

Configurations in a ZnO/Si SAW Structure

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Abstract

The operating frequency corresponding to a given photolithographic limit can be doubled by employing a single phase transducer configuration instead of the conventional interdigital transducer (IDT) configuration. It is found that the signal level due to direct coupling in the single phase structure is reduced by employing a balanced transducer configuration using two single phase delay lines in parallel. Both Rayleigh and Sezawa mode operation in the ZnO-SiO_2-Si structure are described.

The interdigital transducer (IDT) [1] is the most efficient means of exciting and detecting surface acoustic waves (SAW) on piezoelectric media. It consists of a series of metal strips where alternate strips are interconnected as shown in figure 1a. The upper limit on the operating frequency of a SAW device is determined by the capability of the photolithographic technique being used to define the interdigital transducer. A configuration employing a two layer transducer on lithium niobate has been used to double the frequency range for $LiNbO_3$ SAW devices [2]. Herein we describe a technique for doubling the operating frequency for use in the ZnO-on-silicon layered device configuration.

The proposed transducer structure is shown in figure 1b and is referred to as the "single phase" structure [3]. The metal widths and spacings for the single phase structure are $\lambda/2$ (where λ = wavelength of the SAW) while the metal widths and spacings for the conventional IDT structure are $\lambda/4$. Thus, for a given photolithographic limit, one can obtain twice the operating frequency with the single phase structure as opposed to the IDT structure. It is important to note that a single phase transducer in the form of a grating [4], as shown in figure 1c, will improve device yields. The yields improve because electrical shorts between fingers or a break in a finger will alter just a small portion of the transducer's active region.

A Rayleigh mode single phase transducer delay line has been constructed in the $ZnO/SiO_2/Si$ configuration. The Rayleigh waves propagate in the <100> direction on a (100) cut 7 Ω-cm n-silicon substrate. A 0.12 μm SiO_2 film thermally grown on the silicon substrate is covered with a 2.6 μm thick ZnO film deposited by rf sputtering. The transducers consist of 20 aluminum

fingers of equal width and gap (22.9μm) located on top of the ZnO, with an aluminum underlay at the ZnO-SiO_2 interface. The SAW acoustic beamwidth is 1mm and the center-to-center transducer spacing is 12.7mm. Both input and output transducers were tuned with series inductors and there is a convolver gate located between the transducers.

Figure 2 shows the two port insertion loss for the Rayleigh device plotted as a function of frequency. The insertion loss at the synchronous frequency, f_o = 94MHZ, is 25db. This loss value is comparable to that achieved with other MZOS Rayleigh delay lines [5-8]. However it was found that the background signal level, due to direct electromagnetic coupling between the single phase transducers, is only 25db below the response peak. In the IDT structure this direct coupling is often reduced by use of a balanced drive. When using the single phase structure we have found that one can make use of a balanced drive by placing two single phase delay lines in parallel as shown in figure 3. We will refer to this as the separate comb configuration.

In figure 4 the two port insertion loss for a balanced separate comb Rayleigh device is shown. All the parameters are the same as the previously described Rayleigh device except that the beamwidth is now 2mm and there are two convolver gates, one between each half of the transducers. The synchronous insertion loss is 22db and the background noise level is now 60db below the peak transduction. It should be noted that this structure is similar in complexity to a convolver configuration used to obtain self-convolution suppression [9].

In addition to the Rayleigh device, a Sezawa mode balanced separate comb transducer delay line was also constructed. Here the parameters are

the same as for the balanced separate comb Rayleigh device except that the ZnO film is now 10 μm thick, and is deposited by rf magnetron sputtering [10].

The two port insertion loss for the Sezawa device is plotted as a function of frequency in figure 5. The insertion loss at the synchronous frequency, f_o = 114.5MHZ, is 18db, a value comparable with other MZOS Sezawa delay lines [11-12].

The operation of the single phase and separate comb transducers can be examined using a normal mode approach [13] in which one compares the radiation resistance, R_a, and the static capacitance, C_s, of the single phase and balanced separate comb structures to that of the conventional IDT structure. The first comparison made is between a single phase transducer of N fingers and an IDT of N finger pairs that is driven unbalanced. The mark to space ratio is taken as unity for both transducers and they have the same beamwidth. For the single phase structure the radiation resistance is found to be one-half, and the static capacitance is twice that of the unbalanced IDT. Therefore the electrical fractional bandwidth, given by $\Delta f/f_o = 2\pi f_o C_s R_a$, is the same for the single phase structure and the IDT structure driven unbalanced. The second comparison is between a balanced separate comb transducer (with N fingers in each parallel half of the transducer) and an IDT of N finger pairs operated with balanced drive. Again the mark to space ratio is unity in both transducers but now the total beamwidth of the balanced separate comb was taken to be twice that of the IDT. For the balanced separate comb transducer the radiation resistance is one-half and the static capacitance is twice that of the IDT structure driven balanced. Therefore the electrical fractional bandwidth is the same for the balanced separate comb and balanced IDT structures.

In conclusion we have demonstrated a technique for doubling the operating frequency for both MZOS Rayleigh and Sezawa mode transducers without an increase in conversion loss, or in the amount of direct coupling. In addition for devices constructed for a particular frequency, the device yields will be improved with use of the singie phase grating structure. The improvement is due not only to increased metal widths and spacings, but also because shorts between transducer fingers or a break in a finger should have little effect on the performance of the transducer.

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FIGURE CAPTIONS

1a Conventional interdigital transducer configuration

1b Single phase transducer configuration

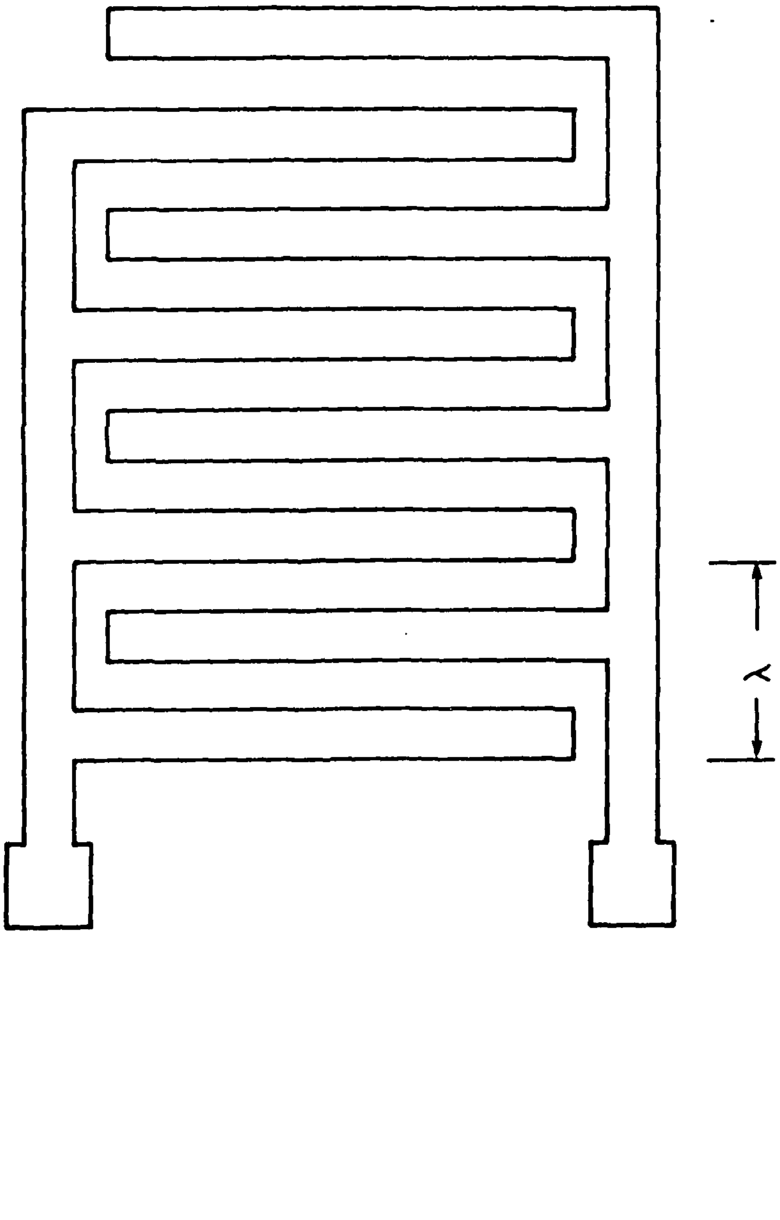
1c Single phase grating transducer configuration

2. Frequency response of single phase transducer Rayleigh device

3. Separate comb transducer device configuration

4. Frequency response of separate comb transducer Rayleigh device

5. Frequency response of separate comb transducer Sezawa device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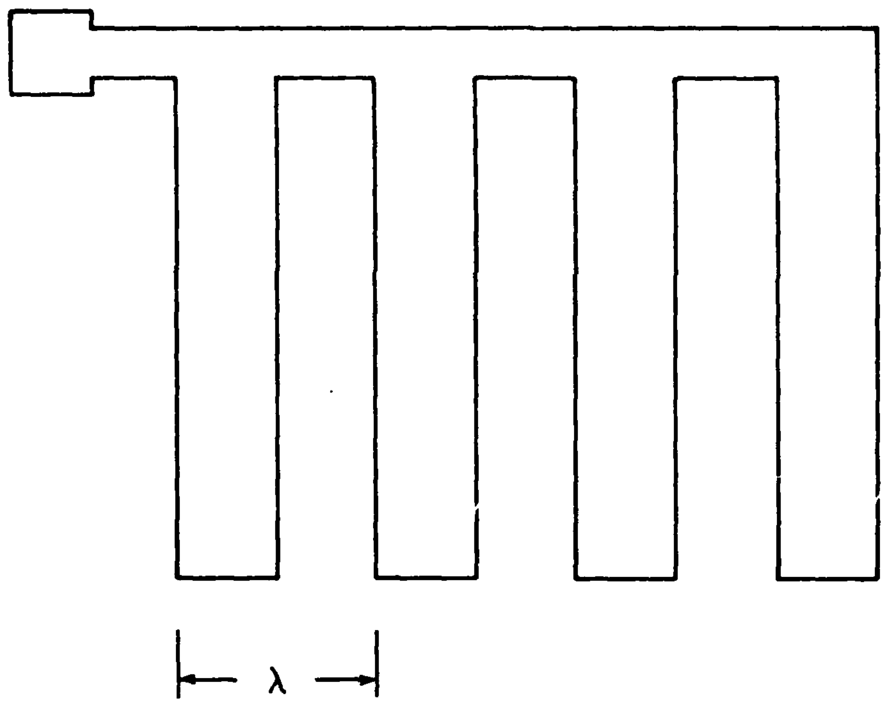
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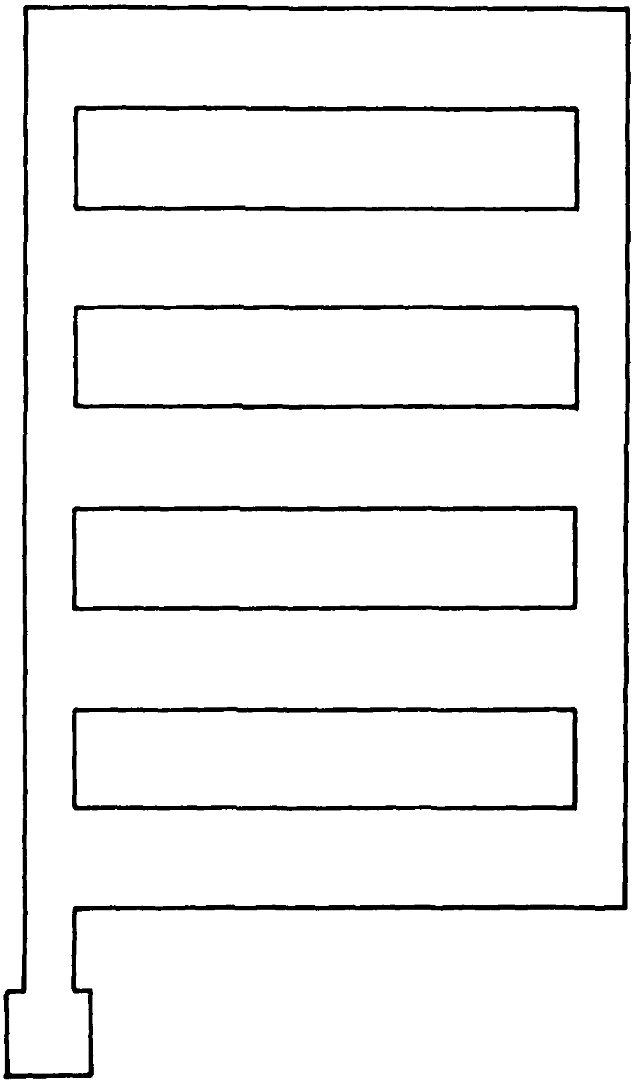

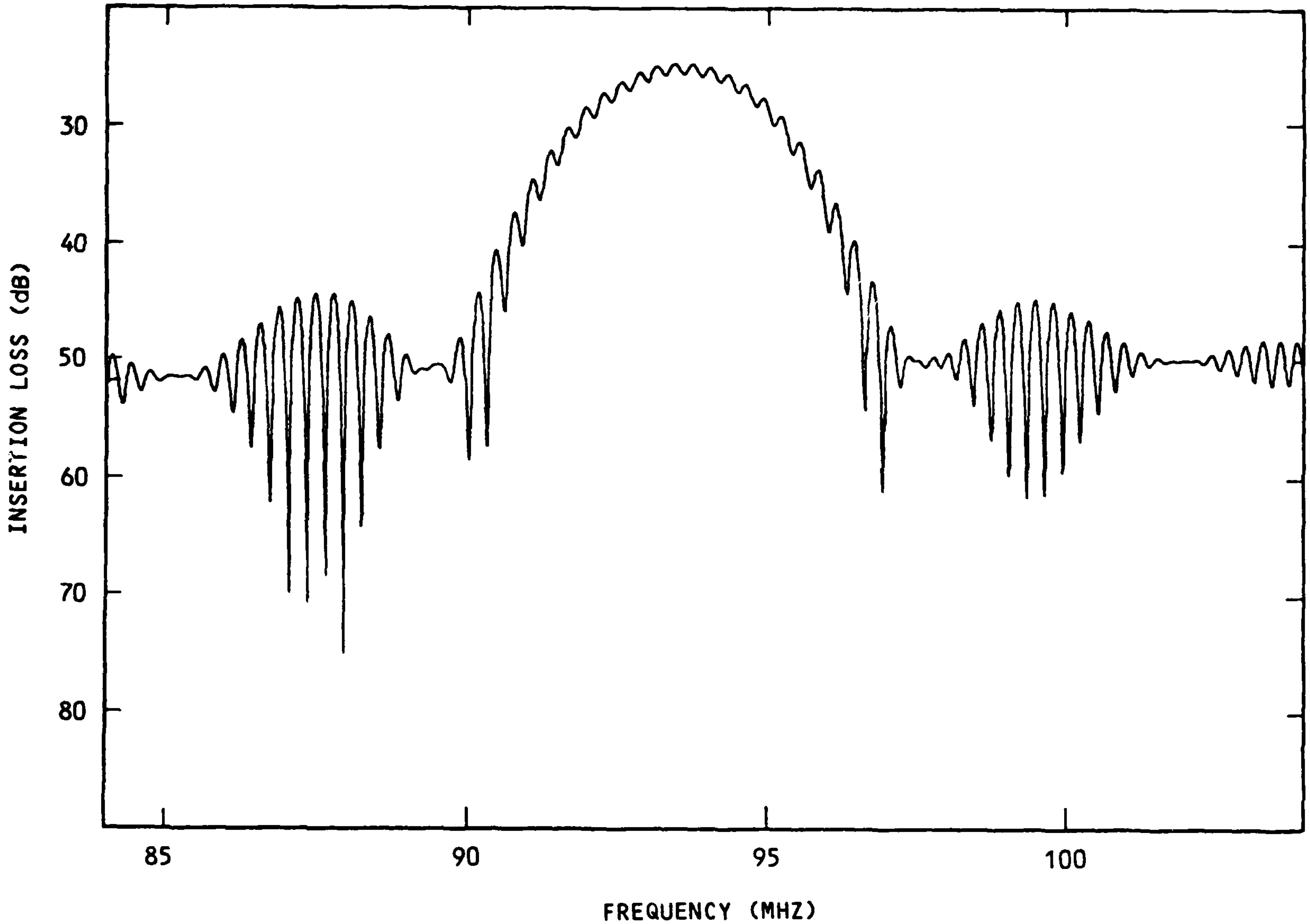
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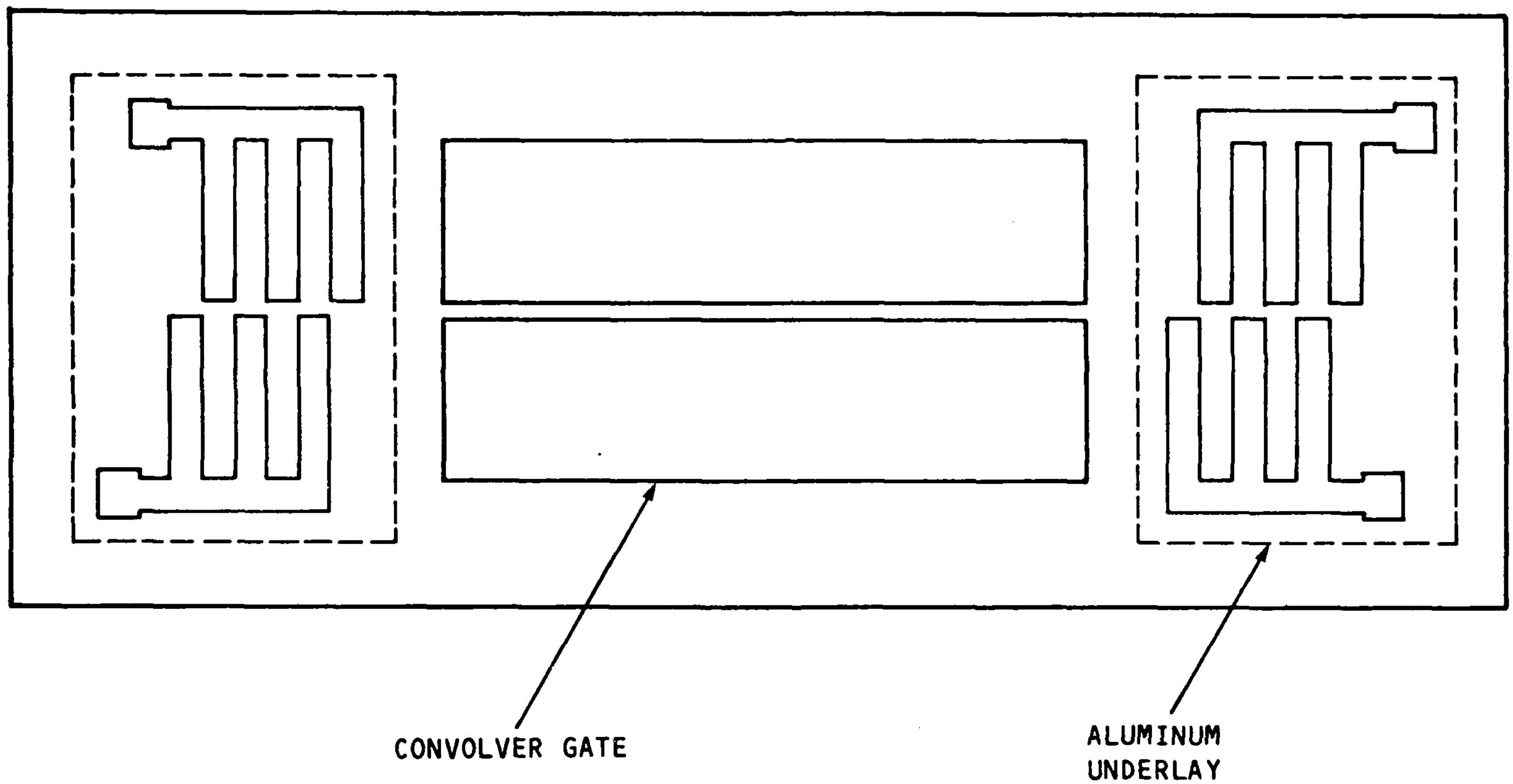
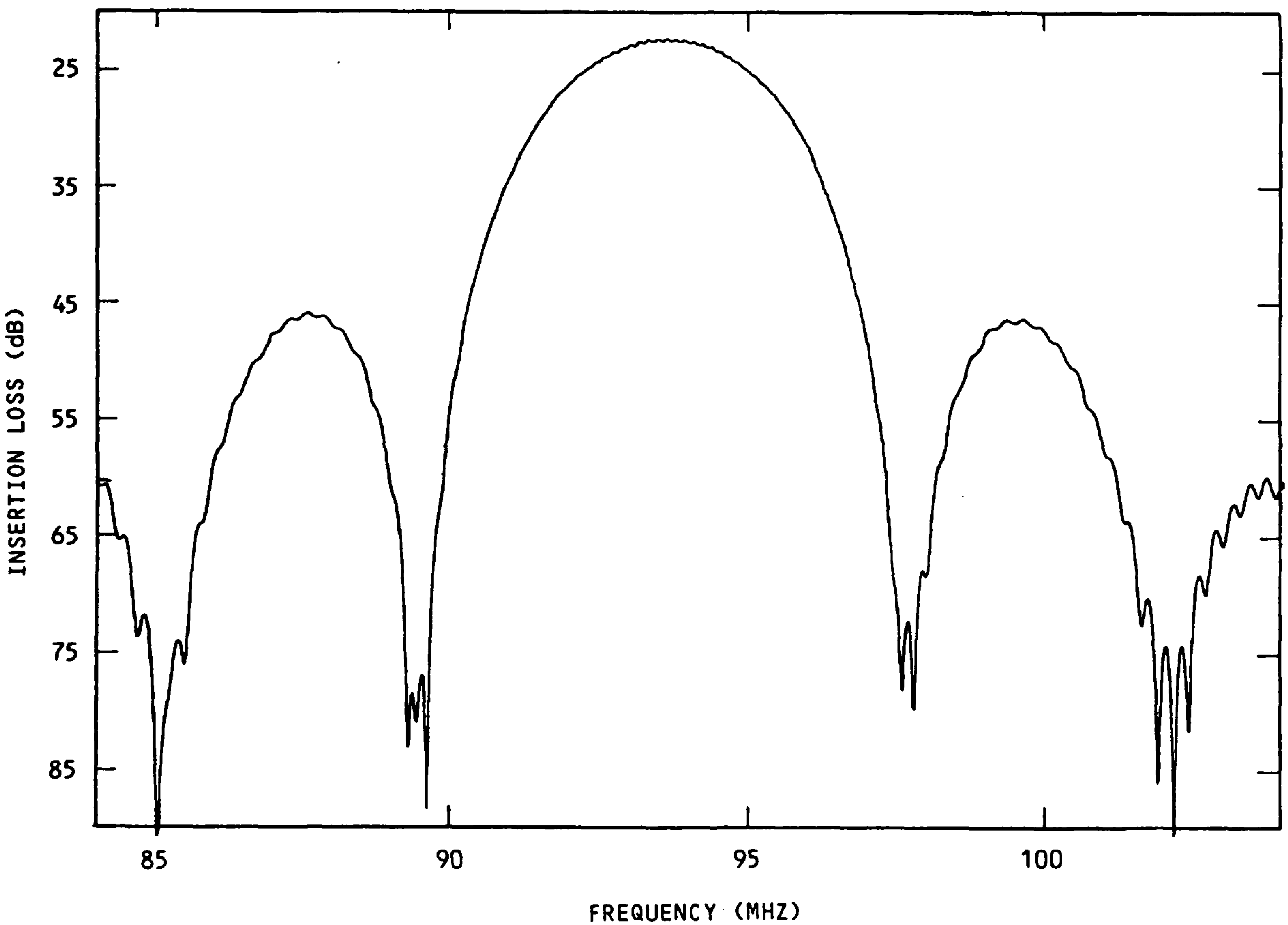


CONVOLVER GATE
ALUMINUM UNDERLAY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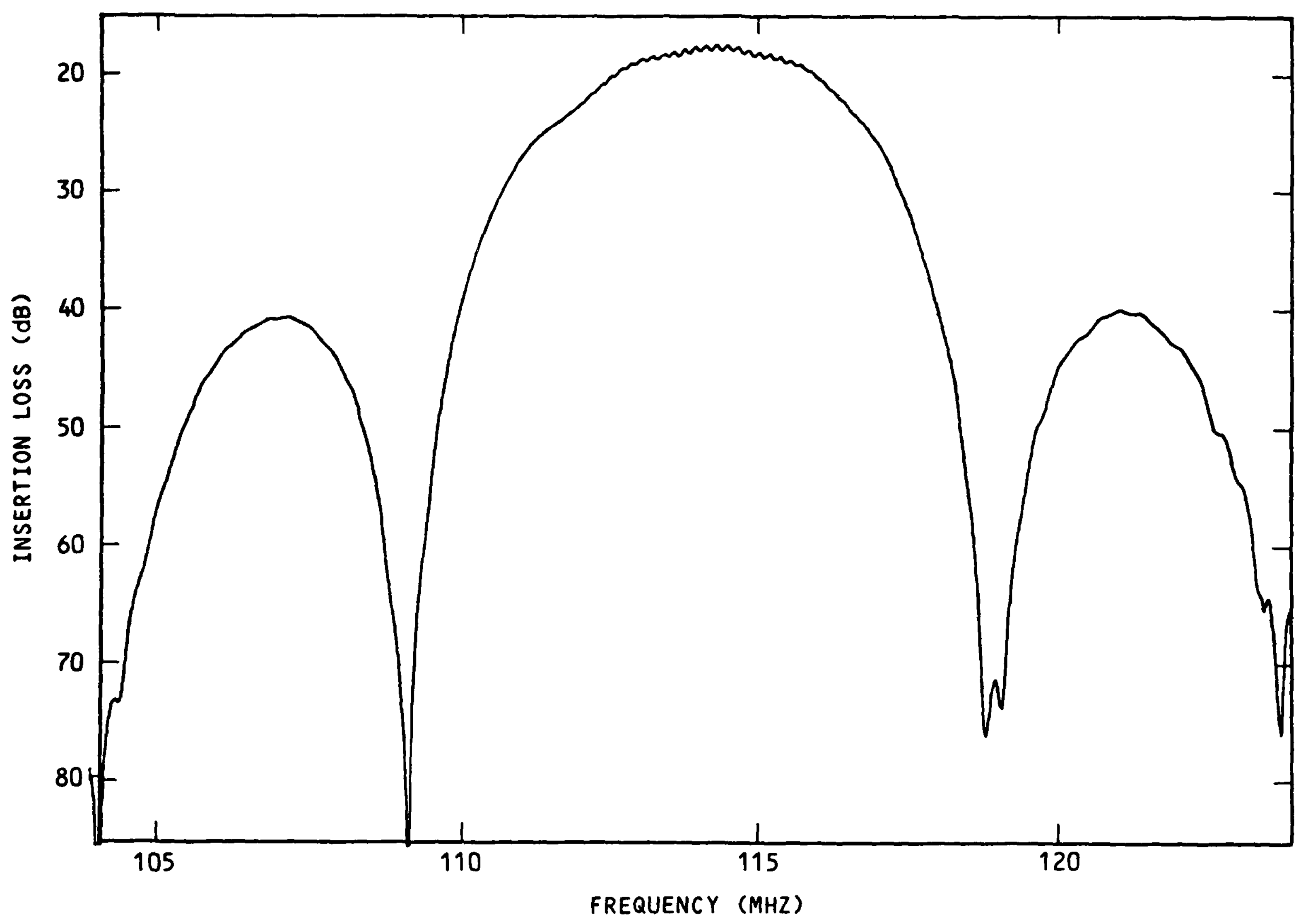

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INSERTION LOSS (dB)
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FREQUENCY (MHZ)

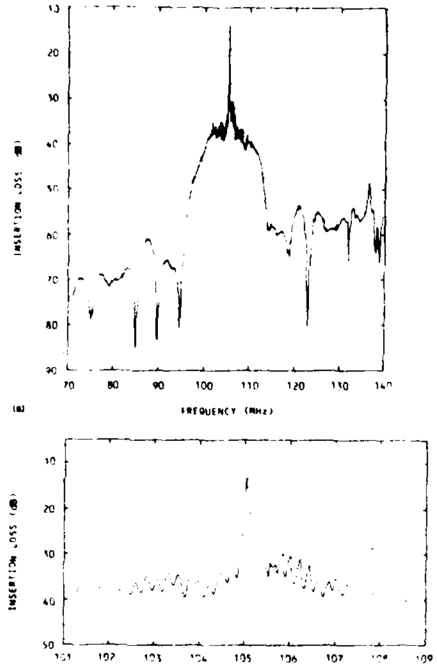

FIG. 2. (A) and (B): frequency characteristics of a two-port SAW resonator fabricated in ZnO-on-Si configuration. 8 finger-pair transducers, 400 shorted Cr/Au reflector strips.

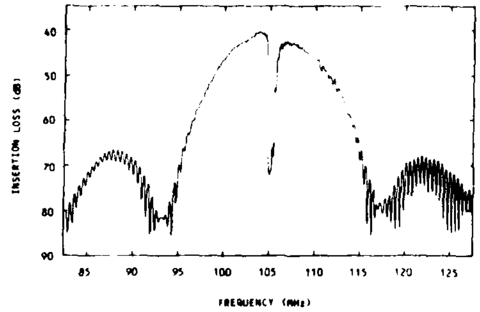

FIG. 3. Insertion loss for transmission through a reflector array consisting of 400 shorted Cr/Au strips.

configurations. During the measurement, the right-hand reflector shown in Fig. 1 was covered with black wax and thereby made inactive. The output was extracted from the additional transducer located at the outer end of the left-hand reflector. For the shorted Cr/Au configuration the 30-dB transmission loss in the reflector stopband seen in Fig. 3 indicates[10] an estimated impedance mismatch of 1% between the shorted Cr/Au strips and the intervening free-propagation surface. Since $\Delta v/v \simeq 0.0032$ for the given ZnO film thickness, this impedence mismatch can be attributed primarily to mass loading by the gold strips rather than to piezoelectric shorting. The resulting 1% reflectivity per strip is comparable to the 1.1–1.8% reflectivity obtained with aluminum on $LiNbO_3$.[10] As also in the case of $LiNbO_3$ devices, it is conceivable that the use of grooves could decrease losses associated with the metal reflectors, yielding significantly higher Q values. In fact, on the basis of the free surface propagation loss reported for the ZnO-on-Si structure,[4] the material Q limitation is approximately 10^4 at 100 MHz.

Another important consideration for many resonator applications is frequency stability with time and temperature. Although aging tests have not been performed, temperature stability was assessed by monitoring the frequency needed to preserve a constant resonant phase over the temperature range -10 to $+50$ °C. The first-order temperature coefficient of frequency was found to be -31 ppm/°C near room temperature. This agrees with theoretical results[11] which also predict that a proper choice of the SiO_2 layer thickness could result in a temperature-compensated device.

In conclusion, surface acoustic wave resonators incorporating a ZnO-on-Si layered structure have been constructed and characterized. The excellent performance of the shorted Cr/Au configuration, in particular, indicates that it is feasible to fabricate moderate-Q VHF-UHF resonators directly on processed silicon wafers for achieving monolithic rf integrated circuits.

The authors are grateful to M. E. Field and C. L. Chen for many helpful discussions and aid in taking measurements, and to J. K. Elliot and R. Young, who laid the groundwork for this project. The research was sponsored jointly by the Air Force Office of Scientific Research under Grant AFOSR-77-3304, National Science Foundation Grant No. ENG 76-1129, and NSF-MRL Grant DMR 77-23798.

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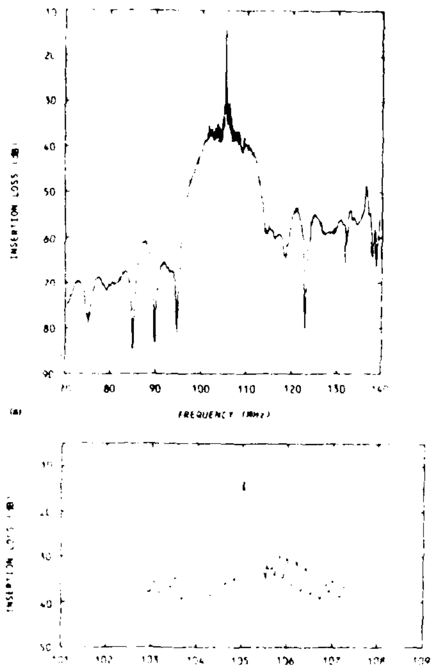

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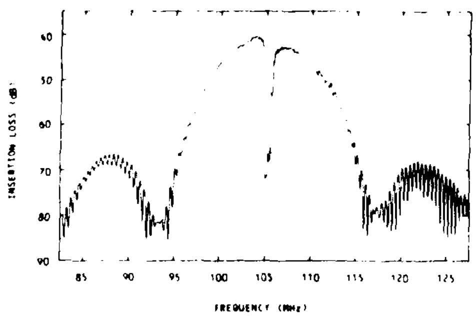

FIG. 3. Insertion loss for transmission through a reflector array consisting of 400 shorted Cr/Au strips.

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In conclusion, surface acoustic wave resonators incorporating a ZnO-on-Si layered structure have been constructed and characterized. The excellent performance of the shorted Cr/Au configuration, in particular, indicates that it is feasible to fabricate moderate-Q VHF-UHF resonators directly on processed silicon wafers for achieving monolithic rf integrated circuits.

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APPENDIX C

HIGH Q, TEMPERATURE STABLE ZnO-on-SILICON SAW RESONATORS

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ABSTRACT

A monolithic SAW $ZnO/SiO_2/Si$ resonator device is reported and several configurations for reflector structures are described. The two-port resonators are found to exhibit Q-values in the 2,000 to 10,000 range depending upon the use of metallic or etched reflector arrays. Temperature compensation through the use of thick thermal oxide layers is also demonstrated.

I. Introduction

Surface acoustic wave resonators fabricated on single crystals of quartz or $LiNbO_3$ have demonstrated applicability as narrow band filters and as frequency control elements in oscillators. The high value of electromechanical coupling make $LiNbO_3$ attractive, while low material loss and temperature stability favor quartz. In this paper we discuss a passive adaptation of SAW resonator technology to the ZnO-on-Si layered configuration.[1,2] The motivation for using this configuration lies in the possibility of constructing VHF-UHF resonators directly on processed silicon wafers for achieving monolithic rf integrated circuits. Moreover, resonators fabricated in the layered configuration can be made competitive with $LiNbO_3$ relative to Q and insertion loss; furthermore, they can be made temperature stable to a degree comparable to ST quartz.

The electromechanical coupling strength, which depends on the piezoelectric ZnO film thickness in the layered structure, is intermediate to that of quartz and $LiNbO_3$.[3] This permits the use of metal strips, as well as grooves etched in the ZnO layer, to form efficient distributed reflectors and to realize low values of insertion loss at the resonant frequency. In section II we discuss the results obtained with aluminum and chrome/gold reflector strips, while section III consider chemically etched groove devices. The results of temperature compensation experiments are discussed in section IV.

II. METAL REFLECTOR DEVICES

Figure 1 displays a ZnO-on-Silicon resonator configuration utilizing metal strip reflector elements. In fabricating the device a 0.1μm-thick SiO_2 layer is thermally grown on the (111) cut silicon substrate and covered with a 0.1μm vacuum-deposited aluminum layer. The aluminum layer both enhances $\Delta V/V$ and avoids electroacoustic attenuation caused by piezoelectric coupling to mobile carriers in the semiconductor.[4] A 1.6μm ZnO film is next deposited by employing rf-magnetron sputter-

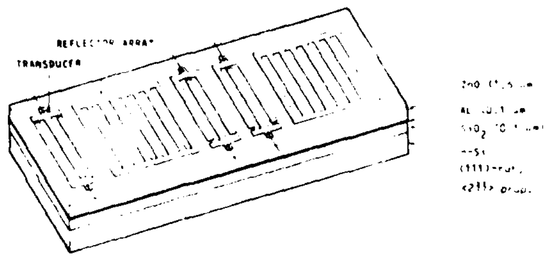

Fig. 1 ZnO-on-Si SAW two-port resonator with metal strip reflectors. External transducer permits measurement of transmission through reflector array. The reflector separation and beamwidth are 30λ.

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ing.[5] The top metallization pattern is formed from either aluminum or chrome gold with interdigital transducers and reflectors being defined in a single photolithographic step. Two port resonators having a single longitudinal mode were fabricated with isolated aluminum, isolated Cr/Au, and shorted Cr/Au reflector strips spaced $\lambda/2$ apart. In order to couple optimally to the standing wave in the cavity, the following spacing between transducer finger centers and the reflector array edge is required:

$$d = \begin{cases} (n/2 + 1/4)\,\lambda_0 & \text{for isolated Cr/Au or shorted Cr/Au reflectors} \\ (n/2)\lambda_0 & \text{for isolated al reflectors.} \end{cases}$$

where λ_0 is the resonant wavelength and n is an integer. Of the three reflector configurations examined, the weakest reflections were observed with the aluminum array, while the strongest reflections were obtained from the shorted Cr/Au array.

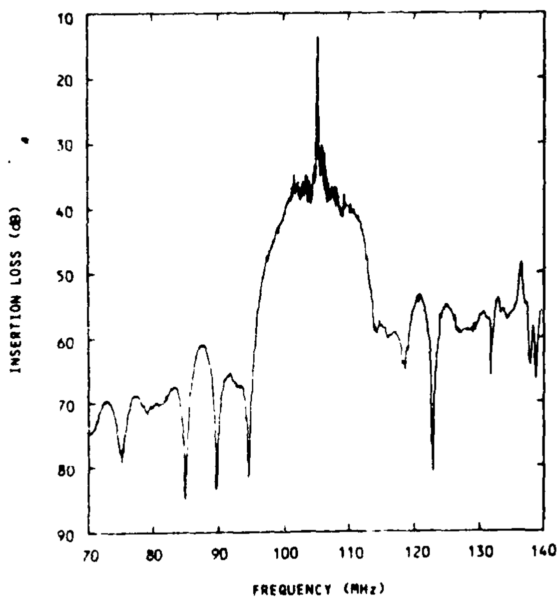

Fig. 2 Frequency characteristics of a two-port ZnO-on-si SAW resonator using Cr/Au reflector strips. 8 finger-pair transducers, 400 shorted Cr/Au reflector strips.

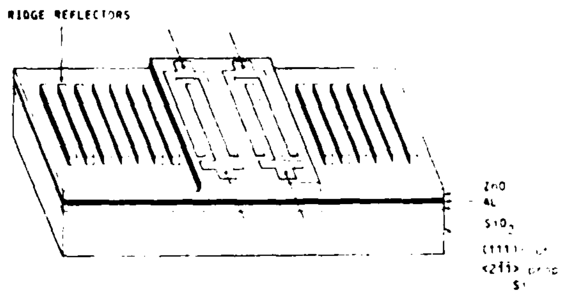

Fig. 3 ZnO-on-Si SAW two-port resonator with etched groove/ridge reflectors. The reflector separation and beamwidth are 30λ.

Figure 2 shows the two port transmission characteristics of a resonator using 8 finger-pair transducers and 400 shorted Cr/Au reflector strips per reflector array.[6] From measurements of transmission through the reflector array the reflectivity per strip is estimated at 1%. Since $\Delta V/V = 0.0032$ for the ZnO film thickness indicated, the dominant reflection mechanism is concluded to be mass loading. The loaded Q of this device is 2500. If the input and output are decoupled from the 50Ω line the resulting unloaded Q is 3100. Also, since the dominant loss mechanism is conductive loss in the metal strips, the efficiency of the Cr/Au reflector array is greater for film thicknesses less than that corresponding to the maximum $\Delta V/V$.

III. ETCHED GROOVE DEVICES

To eliminate losses associated with the conductivity of metal reflectors, resonators were subsequently fabricated using grooves chemically etched in the ZnO layer, (Fig. 3). The fabrication is identical to that of the metal strip resonator described previously up to the point of the top metallization pattern. After sputtering the ZnO film, a top aluminum layer is evaporated from which interdigital transducers and a reflector array mask for subsequent etching of grooves are formed. An alkaline etch is used to define the metallization pattern without damaging the ZnO layer. The region between reflector arrays is then protected with photoresist while a dilute solution of HNO_3 removes

ZnO between the masking strips of aluminum. Finally, the aluminum masking strips and the photoresist used to protect the transducer region are removed. The remaining ZnO ridges act as effective topological surface wave reflectors. This is a result of the velocity perturbation associated with the varying ZnO thickness, as well as the perturbation associated with the geometric discontinuity itself.[7] In contrast to etched groove reflectors formed in single crystals, the velocity increases with moderate groove depths in the ZnO layer due to the decreasing average thickness of the slower ZnO layer. Shimizu and Takeuchi[8] have shown that the effect of groove wall sloping--which is to be expected with chemically etched grooves--has a minor effect on the reflection magnitude at the grating fundamental.

Figure 4 exhibits the two port transmission characteristics of a resonator employing 8 finger-pair transducers and 350 etched grooves per reflector. The groove depth is 0.68μm, a distance nearly half way through the 1.55μm ZnO layer. From transmission measurements on test structures with various groove depths the reflectivity per groove is estimated at 1.26% for the groove depth cited. The reflectivity per groove is found to depend not

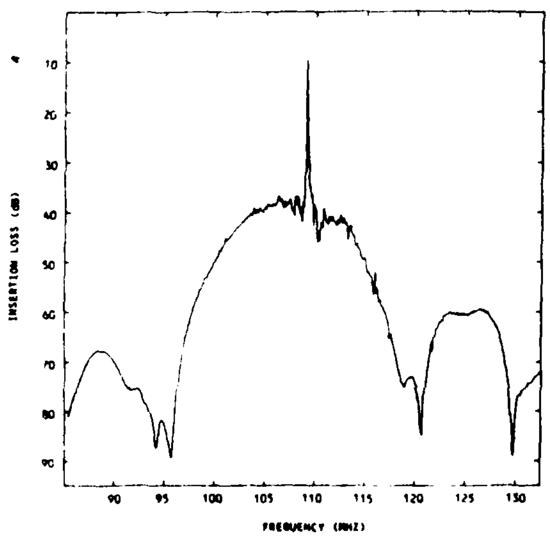

Fig. 4 Frequency characteristics of a two-port ZnO-on-Si resonator utilizing etched groove reflectors. 8 finger-pair transducers, 350 grooves etched .68μm into 1.55μm ZnO layer.

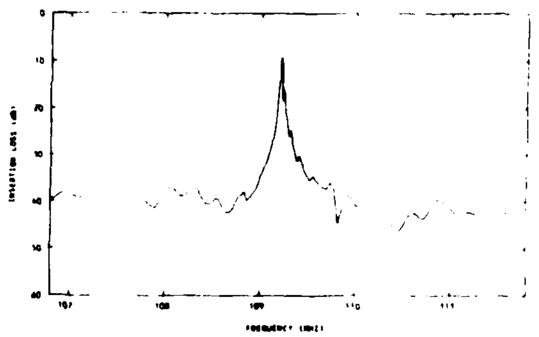

Fig. 5 Expanded view of resonance peak in Fig. 4 showing multiple transverse mode peaks.

only on the normalized groove depth (h/λ) but also on the ratio of the groove depth to the total ZnO thickness.

The loaded Q of the etched device is measured at 6400. The insertion loss of 9 dB at the center frequency indicates an unloaded Q of nearly 10,000. This compares favorably with values reported for both $LiNbO_3$ and quartz devices.[9] The higher Q-value obtained for the configuration shown in Fig. 3 compared to the metal strip configuration (Fig. 1) can be attributed to several factors. The conductive losses in the reflector array have been eliminated, while at the same time we have reduced the transducer reflections by using aluminum rather than Cr/Au. In addition, we anticipate some reduction in diffraction losses of the 30λ wide structure due to waveguiding. That is, in etching the grooves in the ZnO layer we have simultaneously etched the ZnO outside the beamwidth to the level of the groove depth. The region containing the "ridge" reflectors, having a greater average ZnO thickness, therefore has a velocity characteristic lower than that found outside the beamwidth. The result is a greater lateral confinement of the beam - a possible explanation for the number and prominence of transverse mode peaks in Fig. 5.[10]

It is significant to observe that the measured Q-value places an upper limit on the material losses present in the structure of approximately 1.2 dB/cm at 109 MHz. This value is consistent with measurements of free surface propagation loss in ZnO/Si devices reported by Hickernell.[11]

IV. TEMPERATURE COMPENSATION

For many resonator applications such as tuned circuits and oscillator control it is imperative to have a temperature stable resonant frequency. A temperature dependent resonant frequency is caused by changes in both length and surface wave velocity with temperature.

The ZnO-on-silicon configuration of Fig. 1 was found to have a first order temperature coefficient of frequency (TCF) of -31 ppm/°C. It is important to note that, in the layered configuration, the temperature coefficient of stiffness for SiO_2 is opposite in sign to that of ZnO and Si. As a result, several investigators have suggested a proper choice of SiO_2 thickness might result in a temperature compensated device.[12,13] In an attempt to fabricate temperature stable resonators, several SiO_2 thicknesses were tried in the etched groove configuration of Fig. 3. By growing SiO_2 on (111) cut silicon substrates at 900°C in 20 atm. of pyrogenic steam, it is possible to obtain thick SiO_2 films of sufficient surface regularity to permit subsequent sputtering of good ZnO films. Of course, thermal silicon dioxide technology has long since progressed to the point where very accurate control of thickness is attainable.

Figure 6 shows the results of temperature stability tests made on these devices. The first order temperature coefficient of frequency at 23°C is found to increase linearly with normalized SiO_2 thickness. The variation is insensitive to ZnO thickness for etched groove devices. A resonator was built displaying a first order TCF of -1.1 ppm/°C and the Fig. 6 plot indicates a zero TCF value could be achieved at 23°C for $kh_{SiO_2} = 0.475$. Thus, the ZnO-on-Si layered configuration can be compensated to a degree comparable to ST Quartz by simply growing a thermal oxide of approximately $0.076\lambda_0$ thickness. An optimum temperature-compensating thickness of SiO_2 has the effect of decreasing the wave velocity by approximately 4%. In addition, $\Delta V/V$ increases more rapidly with kh_{ZnO} given a thick SiO_2 layer, so that relatively thin ZnO layers could be used in temperature compensated devices. Thin films of high quality are more easily sputtered than are thicker films and the fabrication requirements are thereby relaxed.

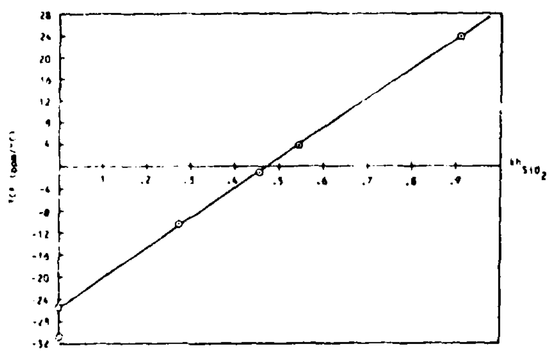

Fig. 6 First order temperature coefficient of resonant frequency vs. normalized SiO_2 thickness for groove resonators on $ZnO/SiO_2/Si$.

V. CONCLUSIONS

We have shown that the ZnO-on-Silicon layered configuration can be used to fabricate high quality, temperature stable resonators. The demonstrated high Q-values obtained with etched ridge/groove devices indicate the compatability of sputtered ZnO films with low-loss applications. It remains to be shown whether aging characteristics are stable enough to take advantage of the demonstrated temperature stability and Q.

VI. ACKNOWLEDGEMENTS

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